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ETHYLENEDIAMINE DINITRATE AND ITS EUTECTIC MIXTURES: A HISTORICAL REVIEW OF THE LITERATURE TO 1982

by

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ABSTRACT

Evaluation of captured WW II ammunition and documents indicates that explosives containing both ethylenediamine dinitrate and ammonium nitrate were used successfully as shell and bomb fills by the Germans. Some mixtures also contained other high explosives and aluminum. Some such formulation may prove useful in the United States arsenal as a safe, inexpensive bomb fill. Formulation and characteristics of the German explosives and their U.S. analogs are tabulated.

INTRODUCTION

The United States Air Force requested in 1981 that Los Alamos National Laboratory study in detail eutectic compositions containing ethylenediamine dinitrate/ammonium nitrate (EDD/AN), hereafter called EA systems. These explosive fills are to be considered to replace TNT, tritonals, and related bomb fills. Recent studies have indicated that EA formulations may be cheaper to produce than comparable bomb fills, and they have improved safety in production and handling without sacrificing performance.¹ To avoid duplicating earlier efforts, the published and unpublished literature was searched for references related to studies of EDD and its mixtures.

HISTORY

Most components of the formulations under consideration have been known and used since the late 1800s. The earliest reference to EA as an explosive or a main component of an explosive mixture was put forth by Stachler² in 1915. Ammonium nitrate and its mixtures

with dinitrobenzene, hexanitrodiphenylamine (HNDPA), dinitronaphthalene, anisole, and similar compounds were used by the Germans as explosives to supplement scarce TNT and AN during World War I (WW I); they used about 10 nitroaromatic compounds in admixture with AN for loading bombs and shells.³

Between WW I and WW II, a multitude of EA systems were studied. A German manufacturer, Dynamit, A.G., patented the preparation of several of these explosive mixtures in 1932.⁴ The Germans also produced RDX and PETN during this period.³ It was not until after WW II that compositions and production and use data became known from captured German documents and from reports by occupation forces.⁵⁻¹⁰ Data from these sources were sketchy and at times contradictory. Little work was done to establish fundamental properties and characteristics of these formulations, because the Germans in wartime were interested only in results—to obtain usable explosives (called *Ersatzsprengstoffe*, substitute explosives). Care was taken to keep the strength of the substitute within 10% of that of the preferred material.⁷

The Germans actually used EDD, which they designated "PH salt" or diamin, and its mixtures in weapons

only during WW II when recurrent shortages of TNT, PETN, RDX, and AN threatened the continued production of ammunition. At that time they began to use aluminum powder to improve the performance of cast explosives.⁷ EDD was used alone for pressed charges, but mixed with nitrates, it depressed the melting point so that formulations could be cast.¹¹ Shortages became critical in August 1944.^{5,11} The amounts of explosives used in each ordnance item are listed in Ref. 7.

Fedoroff, at the Picatinny Arsenal [now the U.S. Armament Research and Development Command (ARRADCOM)] compiled a "Dictionary of Explosives, Ammunition and Weapons — German Section" in 1958.¹¹ He based his compilation on the documents and weapons captured during and after WW II by the Allied Forces. The U.S. Army issued a "Handbook of Foreign Explosives" in 1965.¹²

The French and others were interested enough in some of these explosives to synthesize and mix some compositions and to characterize them.¹³⁻¹⁷ LeRoux¹⁶ analyzed and tested EDD and EA from captured German weapons. He stated that, indeed, EDD could replace TNT or Melinite [mostly picric acid (PA)] in case of shortages of toluene or benzene; EA could substitute for Amatol 50/50 (TNT/AN 50/50).

Re-examination of the behavior of EDD- and EA-based eutectics by Hershkowitz and Akst at Picatinny Arsenal several years ago led to studies of improved performance of EA-containing bomb fills and other mixtures without increasing costs or sacrificing safety and energy.¹⁸ Voreck at ARRADCOM has been studying EA systems, some containing nitroguanidine (NQ). Researchers at Los Alamos National Laboratory joined this effort on a small scale about five years ago. Impact sensitivities, melting points, critical temperatures, and performance data were determined for numerous EA systems; other eutectics containing AN were also discovered.¹⁹⁻²²

SUMMARY OF FORMULATIONS AND PROPERTIES

The information gleaned from the literature is summarized below; details can be found in the references. Most of the WW II reports are available from the Library of Congress, Washington, D.C. Compositions, uses, and properties of the formulations are tabulated in Appendix A with the appropriate sources.

Formulations

Conventional materials for bomb and shell fillings became scarce during WW II, so the Germans tried and then used substitutes for TNT, AN, and RDX in conjunction with other materials, such as guanidine nitrate (GuN) and aluminum.¹¹ Proportions were varied to enhance performance and safety and to facilitate loading. Of the approximately 40 mixtures formulated and studied over the years, only about 15, all German, have been used in munitions, but these munitions were not necessarily deployed in the field; the mixtures and their weight per cents are^{7,8,10,11}

Amatol 41 (actually an Ammonite) —

AN/EDD/RDX/CaN^a/Wax 52/30/10/6/2.

Ammonite 43B —

AN/EDD/RDX/CaN/TNT/GuN/PETN/Vultanol^b 55/7/5/7/10/10/10/2/0.3.

Ammonite H-5 — AN/EDD/RDX/CaN/NaN^c

55/10/20/10/5.

Ammonite H-5K — AN/EDD/RDX/CaN

30/20/20/30.

Ammonite H-5T — AN/EDD/RDX/CaN/KN^d/NaN

50/10/20/10/5/5.

Ammonite H-15 — AN/EDD/RDX/CaN/NaN

60/8/13/12/7.

EDD — 100.

FP^e — AN/EDD/RDX/CaN/Wax 55/30/8/5/2.

FP 83 — EDD/HE,^f

FP 84 — AN/EDD 45/55.

Special FP 84 — AN/EDD/CaN 46/46/8.

S-16 — AN/EDD/Al/RDX/KN/NaN

32/10/40/10/2/6.

S-18 — S-17 matrix (TNT/RDX/Al 50/10/40)/S-16 pellet 60/40.

S-22 hexa — AN/EDD/Al/KN/NaN/HNDPA^g

45/14/15/3/9/14, and

S-22 hexo — AN/EDD/RDX/KN/NaN

55/14/14/8/9.

Aluminized formulations proved particularly effective in submarine weapons.⁹ The aluminum powder used had to be fine enough to pass through a 200-mesh sieve; it was aged in open trays before packing to prevent overheating and possible ignition.¹⁰ Impurities introduced by aluminum frequently caused bubbling and

^aCaN — calcium nitrate

^bVultanol — emulsifier

^cNaN — sodium nitrate

^dKN — potassium nitrate

^eFP — fill powder

^fHE — high explosive

^gHNDPA — hexanitrodiphenylamine

evolution of gases, particularly ammonia.¹⁰ The most prevalent impurities were copper, magnesium, manganese, silicon, and zinc. Gas evolution caused by moisture was eliminated by sealing off the fills with nonnitrate compositions.¹⁰

Vultanol, an emulsifying agent, was added to prevent separation of the TNT in Ammonite 43B.⁹ The AN stabilized GuN and TNT against decomposition at higher temperatures in this formulation. Volume expansion of cast charges undergoing large temperature fluctuations (between -40 and +70°C) was prevented by adding 5-10% KN to AN to form mixed crystals.⁹ Adding NaN, KN, or CaN also enabled the substitution of TNT and countered shrinkage of the charges by eliminating phase changes in AN.¹¹ S-16 was developed specifically to eliminate the volume change caused by the phase change of AN at 32°C.¹⁰ The 2% KN in this formulation reduces the tendency of such castings to decrease substantially in density as temperature increases.⁶ The other formulations found in the literature are also listed in Appendix A.

Thermal Stability

Safety requirements have become increasingly more stringent over the years, so French and U.S. scientists used heating tests to establish safe operating temperatures for EA systems. EDD began to decompose at 130-140°C by turning brown; liquefaction was observed around 180°C; and gas evolution was noted at 205°C.¹⁴ At 230°C only nitrous vapors and carbonaceous residue remained.¹⁶ Adding hydrazine nitrate (HyN) or AN to EDD seemed to improve the thermal stability of the mixtures: EA/HyN 50/50 began to react at 215°C, EA at 210°C.¹⁷ Decomposition with much gas evolution and some brown residue was complete at 270°C and 300°C, respectively.

Researchers at Los Alamos evaluated various EA formulations with stabilizers and found KN to be the most satisfactory: EA/KN formulations are designated as EAK. They established the thermal stability of X-0368 (AN/EDD/KN 50/42.5/7.5) for fairly large melts in a 203-mm-i.d. by 254-mm-high steel container. Reaction was observed at 200°C, and the sample continued to self-heat until all reaction products were consumed. This compares well with the small-scale French results, where EA started to react around 210°C.^{17,21} The critical temperature (T_c) of X-0368 was

estimated from a thermal hazards model developed by R. N. Rogers and J. L. Janney. The worst-case model for an unstirred 3-m-diam melt kettle estimates the maximum safe temperature as 111°C, for a stirred kettle as 158°C. Measured T_c for an 0.083-cm-thick slab was 244°C. All T_c data are dependent on sample size as shown in Fig. 1. (Ref. 21).

Impact Tests

The French also conducted "shock sensitivity" tests on captured German ammunition, using 10- and 30-kg weights in drop tests and impact velocities of 470 to 1000 m/s in bullet impact tests. EDD and EA were slightly less sensitive than TNT or Amatol 50/50 in these tests.¹⁶ Recent U.S. drop-weight impact tests (2.5 kg) on EA showed it to be slightly less sensitive than TNT.¹

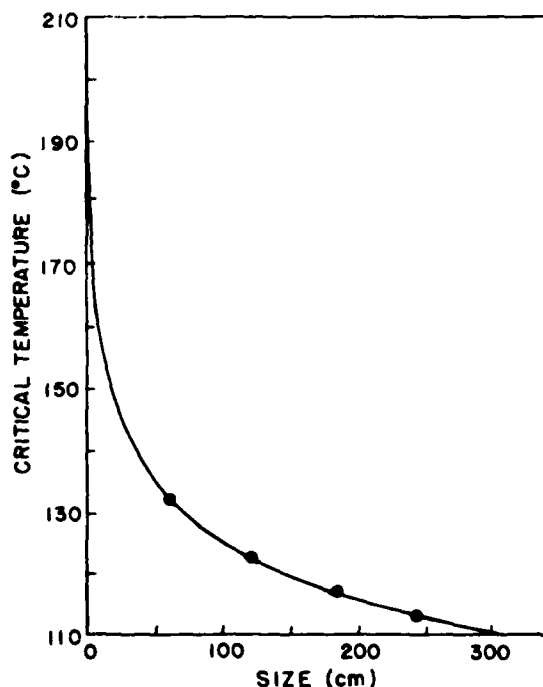


Fig. 1. Critical temperature versus size (diameter of casting kettle) predictions for pure EAK according to a Frank-Kamenetskii (worst-case) model with $E = 47$ kcal/mole, normalized to the experimental measurement ($T_c = 244^\circ\text{C}$ for an 0.083-cm-thick slab). The model assumes no convective cooling or stirring.

Performance

EDD was used alone or slightly phlegmatized* in small armor-piercing (AP) shells and anticoncrete ammunition.^{9,10} It was comparable in behavior to Amatol 50/50 and was, therefore, a suitable substitute for TNT in case of toluene shortages.¹⁶ TNT equivalents are given as pounds of TNT required to equal 1 lb of S-16 or S-17.^{7,10}

Formulation	TNT Equivalent (lb)	
	Weight	Volume
S-16	2.53	2.97
S-17	2.12	2.50

Adding EDD to formulations containing AN improves performance.¹⁸ Detonation behavior of EA is like that of typical, monomolecular explosives, and reaction and energy release can be fast ($<1 \mu\text{s}$).¹

PRODUCTION

Filling plants were operated as part of the production plants. These installations consisted customarily of buildings and magazines grouped in dense forests that provided camouflage protection.^{5,6} A large, single-floor pouring room (two stories high) with several bays was attached to a three-floor (three stories high) production building. The bays had concrete walls 30 to 76 cm (1 to 2-1/2-ft) thick; a 9.1-m (30-ft)-wide passageway acted as buffer, except that newly filled shells were transported through these corridors to cooling areas.¹⁰ Some of these buildings were also used for storing empty shells, for drilling, and for reclaiming explosives from discarded weapons. As many as four melt-loading units could be housed in one building in separate bays. The starting materials were carried to the top floor of the production building in elevators. AN/TNT formulations were loaded successfully into shells by an automated extrusion process, but loading of ammonites by extrusion resulted in explosions.¹⁰

Rudolf Meyer, in charge of filling operations at Kruemmel, stated that worm-filling was unsafe, so the Germans developed melt-loading. Preformed, pressed

*Desensitized with wax or other suitable substance(s).

charges were also used extensively.⁶ Ninety per cent of German ammunition was filled by melt-casting.¹⁰ Recovered molten explosives were often cast into biscuits or chunks, which were stuck into the melt during bomb loading up to 50-60% of total charge weight. These chunks or biscuits helped reduce shrinkage and cavities, besides conserving short supplies.^{6,7} Production and loading of S-16 are described in Appendix B.

The melts were dispensed through the floor into smaller melt kettles or through a thick concrete wall into various pouring devices or directly into bombs. Small precast chunks were pushed into the melt to increase solids loading.

SAFETY

Fire danger from external causes was extremely low because of high humidity. Buildings were constructed of reinforced concrete with one blast wall.^{5,6} In the buildings, accidental fires and explosions were traced to excessive heating or improper drilling or handling of the charges.^{6,7,10} The lack of highly finished surfaces on German steel and bronze tools, compared with U.S. tools, may have been a contributing factor.¹⁰ Several large explosions happened in two filling houses and during storage of many tons of explosives; sympathetic detonation seems to have occurred in at least one case, where 18 tonnes (20 tons) of what may have been S-22 exploded from unknown causes and caused 3.6 tonnes (4 tons) to explode in an adjacent building. A shell loaded with Ammonite H-5 caused a minor explosion.⁶ These two incidents were listed among the 15 explosions reported during the first seven months of 1944.⁶ The absence of floor coverings over the concrete floors caused some accidents.^{5,6} Many plants were said to have had at least one explosion.⁵ Specific reports on accidents have not been found, except for the statements quoted here.

Most explosions of cast charges during handling or transportation were thought to have been caused by separation of unstable and, therefore, supersensitive crystals during cooling; but handling and transport of warm, unsolidified cast charges were no more hazardous than those of cool, solidified charges.⁷

Safe container materials were PVC and epoxy resins. Flammable materials should not be stored with or adjacent to AN containers or to ammunition loaded with AN-containing mixtures, because flammable materials increase AN's thermal sensitivity.¹²

Some protection was provided to the workers by gloves, skin creams, talc, and similar personal items.⁶ Fresh air circulation was provided in some areas.⁶ Protective footwear was not worn.⁵

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APPENDIX A

TABLE A I. Explosives Formulations, Selected Properties, and Uses (Listed by Increasing EDD Weight Per Cent).

Designation	EDD	A	Al	RDX	CaN	KN	NaN	Other	Comments	References
Ammonite 43B ^a	5	55.7	...	7.	10	...	...	TNT 10 GuN 10 PETN 2 Vultanol 0.3	$\rho = 1.61 \text{ g/cm}^3$, casting $T = 105^\circ\text{C}$; fragment density ^b is 37-38 m; used in projectiles	7, 9, 12
Ammonite H 15 ^a	8	60	...	13	12	...	7	...	Used in projectiles	7, 12
Ammonite ^a	10	55	...	20	10	...	5	...	$\rho = 1.53 \text{ g/cm}^3$, casting $T = 108^\circ\text{C}$; fragment density is >400 m	9
Ammonite H 5 ^a	10	55	...	20	10	...	5	...	$\rho = 1.49\text{-}1.50 \text{ g/cm}^3$, $D = 5.9 \text{ km/s}$; ignition $T = 214^\circ\text{C}$; used in mines and projectiles	5, 7, 10, 11, 12
Ammonite H 5T ^a	10	50	...	20	10	5	5	...	Used in mines and projectiles	7, 12
S 16 ^a	10	32	40	10	...	2.0	6.8	...	$\rho = 1.86 \text{ g/cm}^3$ pressed, ~1.70 poured in large charges; $mp = 105^\circ\text{C}$, $D = 7.6 \text{ km/s}$; used in mines and torpedoes	7, 11, 12
	10	90	...	...	...	...	...	...	Freezing point (fp) = 151°C ; solid at 132°C	13
S 22 hexa ^a	14	45	15	...	...	3	9	HNDPA 14	Sometimes exploded during projectile loading	5, 10, 11
S 22 hexo ^a	14	55	...	14	...	8	9	...	Used in torpedoes	5
Ammonite M18H ^a	15	51	...	20	5	...	...	MgNO ₃ 9	Ignition $T = 220^\circ\text{C}$	10
Ammonite M18Np ^a	15	51	...	...	...	5	...	MgNO ₃ 9 PETN 20	Ignition $T = 185^\circ\text{C}$	10
Ammonite H 5K ^a	20	30	...	20	30	...	...	...	Used in projectiles	7, 12
	20	20	...	...	...	...	...	HMX 60	$\rho = 1.795 \text{ g/cm}^3$; $mp = 102^\circ\text{C}$	20
	20	60	...	20	...	...	...	...	TMD = 1.712 g/cm^3 ; $D = 8.68 \text{ km/s}$ (Tiger calc.)	18
	26	34	...	40	...	...	...	...	TMD = 1.718 g/cm^3 , $D = 8.69 \text{ km/s}$ (Tiger calc.)	18
	26	34	...	...	...	...	...	TNT 40	TMD = 1.661 g/cm^3 , $D = 7.91 \text{ km/s}$ (Tiger calc.)	18
	29.3	42	...	...	...	...	...	DETN 28.7	$\rho = 1.63 \text{ g/cm}^3$, $mp = 87^\circ\text{C}$; $D = 5.8 \text{ km/s}$	20

TABLE A I. (continued)

Designation	EDD	A	Al	RDX	CaN	KN	NaN	Other	Comments	References
	30	70							fp = 122°C	13
	30	30		40					$\rho = 1.66 \text{ g/cm}^3$, $D = 7.38 \text{ km/s}$; TMD = 1.712 g/cm ³ , $D = 8.65 \text{ km/s}$ (Tiger calc.)	18
	30	30						HyN 40	$\rho = 1.56 \text{ g/cm}^3$, $D = 1.97 \text{ km/s}$ with low confinement, but unstable	17
Amatol 41*	30	52		10	6			Wax 2	Fragment density is 40 m; used in bombs	7, 8
FP*	30	55		8	5			Wax	Explosive proper similar to Amatol 50/50 stable; used as bursting charge	11
	30							TNT 70	$\rho = 1.63 \text{ g/cm}^3$, $D = 3.7 \text{ km/s}$; TMD = 1.675 g $D = 7.77 \text{ km/s}$ (Tiger calc.)	18
	30.9	39.9						ADNT 29.2	$\rho = 1.607$, $D = 7.66 \text{ km/s}$	19
	35	35						NQ 30	$\rho = 1.69 \text{ g/cm}^3$; mp = 97°C; $D = 5.67 \text{ km/s}$	20
	35	45		20					$\rho = 1.62 \text{ g/cm}^3$, $D = 6.16 \text{ km/s}$; $\rho = 1.73 \text{ g/cm}^3$, $D = 6.7 \text{ km/s}$	1
	36.2	36.2	14.8	12.8					$\rho = 1.73 \text{ g/cm}^3$, $D = 6.7 \text{ km/s}$	1
	38	48						TETN 14	$\rho = 1.65 \text{ g/cm}^3$, mp = 99°C; $D = 6.1 \text{ km/s}$	20
	38.8	50.1						ADNT 11	$\rho = 1.535 \text{ g/cm}^3$, $D = 7.87 \text{ km/s}$ (BKW calc.)	19
	38.8	42.6				7.6		ADNT 11	$\rho = 1.626 \text{ g/cm}^3$, $D = 8.34 \text{ km/s}$ (BKW calc.)	19
	40	40		20					$\rho = 1.61 \text{ g/cm}^3$, $D = 6.39 \text{ km/s}$; TMD = 1.684 g/cm ³ , $D = 8.59 \text{ km/s}$ (Tiger calc.)	18
	40			60					TMD = 1.713 g/cm ³ , $D = 8.52 \text{ km/s}$ (Tiger calc.)	18
	40	60							TMD = 1.671 g/cm ³ , $D = 8.54 \text{ km/s}$ (Tiger calc.)	18
	40	55						MAN 5	Casting T = 93°C	4
	40	50						HyN 10	$\rho = 1.53 \text{ g/cm}^3$; irregular, incomplete detonation	17
	40	40						HyN 20	$\rho = 1.51 \text{ g/cm}^3$, $D = 1.3 \text{ km/s}$	17

TABLE A I. (continued)

Designation	EDD	A	Al	RDX	CaN	KN	NaN	Other	Comments	References
	40.3	40.3	5.2	14.2					$\rho = 1.67 \text{ g/cm}^3$, $D = 7.1 \text{ km/s}$	1
	42.5	42.5		15					$\rho = 1.60 \text{ g/cm}^3$, $D = 7.1 \text{ km/s}$	1
	42.5	36.1		15		6.4			$\rho = 1.64 \text{ g/cm}^3$, $D = 5.6 \text{ km/s}$	1
	42.64	42.67				7.62		NQ 7.07	$\rho = 1.67 \text{ g/cm}^3$, mp = 97°C , $D = 5.25 \text{ km/s}$	20
NB 79	42.8	57.2							$\rho = 1.50 \text{ g/cm}^3$, $D = 5.52 \text{ km/s}$ at $P = 400 \text{ kg/cm}^2$; peak at $\rho = 1.35 \text{ g/cm}^3$, $D = 6.18 \text{ km/s}$ at $P = 250 \text{ kg/cm}^2$	14
	44	56							$\rho = 1.58 \text{ g/cm}^3$, $D = 5.52 \text{ km/s}$; TMD = 1.665 g/cm^3 , $D = 8.57 \text{ km/s}$ (Tiger calc.)	18
	45	55							mp = 105°C ; explosive properties similar to TNT. Amatol 50/50; casting $T = 105^\circ\text{C}$	4, 8
FP 20 ^a	45	53.5	1.5						Use unknown	11
Ammonite ^a	46	46			8				Fragment density is 39.40 m	8
Special FP 84 ^a	46	46			8				Used in field howitzer shells with central burster tube	7, 12
X 0368	46	46				8			$\rho = 1.636 \text{ g/cm}^3$, $D = 5.7 \text{ km/s}$; stable < 200°C	22
FP 86 ^a	46			18				Wax 36	Pressed in block, wrapped in waxed paper, put in aluminum containers	11
	49	57							$\rho = 1.658 \text{ g/cm}^3$, mp = 103°C , $D = 5.2 \text{ km/s}$	20
	50	42.5				7.5			$\rho = 1.607 \text{ g/cm}^3$, $D = 5.28 \text{ km/s}$	22
	50	50							$\rho = 1.62 \text{ g/cm}^3$, $D = 5.99 \text{ km/s}$; performance better than Amatol 50/50; fp = 100°C at $\rho = 1.633 \text{ g/cm}^3$; $\rho = 1.55 \text{ g/cm}^3$, $D = 5.19 \text{ km/s}$; $\rho = 1.57 \text{ g/cm}^3$, $D = 5.6 \text{ km/s}$; TMD = 1.657 , $D = 8.52 \text{ km/s}$ (Tiger calc.)	1, 13, 15, 18
FP 84 ^a	55	45							Used in shells as bursting charge	11
	56	24		20					$\rho = 1.51 \text{ g/cm}^3$, $D = 6.93 \text{ km/s}$; TMD = 1.663 g/cm^3 , $D = 8.44 \text{ km/s}$ (Tiger calc.)	18

TABLE A I. (continued)

Designation	EDD	A	Al	RDX	CaN	KN	NaN	Other	Comments	References
	60			40					$\rho = 1.64 \text{ g/cm}^3$, $D = 7.81 \text{ km/s}$; TMD = 1.672 g/cm^3 , $D = 8.38 \text{ km/s}$ (Tiger calc.)	18
	60	40							$\rho = 1.47 \text{ g/cm}^3$, $D = 5.8 \text{ km/s}$; $f_p = 112.5^\circ \text{C}$	13, 18
	60							TNT 40	TMD = 1.618 g/cm^3 , $D = 7.79 \text{ km/s}$ (Tiger calc.)	18
	70	30							$\rho = 1.51 \text{ g/cm}^3$, $D = 5.78 \text{ km/s}$; TMD = 1.632 , $D = 8.34 \text{ km/s}$ (Tiger calc.)	18
	80	20							$\rho = 1.48 \text{ g/cm}^3$, $D = 5.38 \text{ km/s}$; $f_p = 135.5^\circ \text{C}$; TMD = 1.619 g/cm^3 , $D = 8.25 \text{ km/s}$ (Tiger calc.)	13, 18
	90	10							$f_p = 148^\circ \text{C}$; obvious EDD decomposition	13
EDD	100								$\rho = 1.55 \text{ g/cm}^3$, $D = 6.77 \text{ km/s}$; TMD = 1.595 , $D = 8.09 \text{ km/s}$ (Tiger calc.); $\rho = 1.577 \text{ g/cm}^3$, $mp = 185^\circ \text{C}$; cast; used in anti-concrete and AP shells; $\rho = 1.58 \text{ g/cm}^3$, $D = 7.3 \text{ km/s}$	1, 8, 9, 13, 18 14, 15, 20
FP 83 ^a	Mixture of EDD with other HE, e.g., RDX								Used in bursting charge	11
S 18 ^a	S 17 (TNT/RDX/Al 50/10/40) matrix/S 16 pellet 60/40								Used in underwater mines and torpedos	8, 10
S 24 ^a	S 22/S 20 (TNT/DINA/Al/HNDPA 40/15/15/30)									8, 11
S 25 ^a	S 22/S 23 (TNT/Diamine/Al/HNDPA 40/15/15/30)									8, 11
S 30 ^a	S 22/S 29 (TNT/Al/HNDPA 54/16/30)									8, 11
S 31 ^a	S 22/S 1 (TNT/Al/HNDPA 60/16/24)									8, 11

^aGerman explosive.^bFragment density. This test was developed and used by the Germans during WW II to establish a relationship between effective weight, velocity, range, and number of fragments and the type of explosive as well as the type and thickness of the casing. Results were given as one penetration per square meter.¹¹^cNo designation given.

APPENDIX B

Preparation of 500 kg of S-16 Explosive.^{6,7,10}

The mix is prepared in two 250-kg increments.

The steam pressure is set for 118°C maximum.

The equipment must be free of yellow metal; aluminum is used instead.

Water and high humidity must be excluded because these formulations are very hygroscopic.

One bucket of melt is left in the kettle for the next batch, except that all equipment, if used continuously, must be cooked out with water every 24 hours.

Initial mixing takes place in the upper melt kettle on the third floor. The first portion consists of

50 kg EDD,

30 kg NaN,

10 kg KN, and

160 kg AN.

The EDD is poured into the kettle first, followed by NaN, KN, and finally, AN. Each ingredient is added by hand (a 1-cm-thick layer at the start) until the molten material reaches the stirrer. About 20 min of stirring is required for the nitrate mixture to melt completely at 113-115°C. After all the starting material has been added, the temperature is allowed to reach 113°C with

continued stirring until the mixture is clear and dark. Longer stirring is needed if the fluid appears milky. The melt is then allowed to stand for 5 min without agitation so that impurities may rise to the surface as froth, which will then become the one bucket remaining in the kettle after the melt is drawn off. This froth will further depress the melting point in subsequent batches.

For the second step, this 250-kg melt is drawn down into the lower melt kettle where the second lot is added with continued agitation at 100°C or above. First, the 200 kg of aluminum powder is added from a closed container to avoid dust in the atmosphere, then the 50 kg of RDX. The aluminum powder was aged in open trays to prevent overheating and possible ignition.¹³ The entire batch is stirred for about 10 min to obtain thorough mixing and to reach 113°C; then it is left standing in the kettle for a few minutes without agitation to allow entrained air to escape from the melt. S-16 was poured into pellet trays to a maximum thickness of 2 cm at a pouring temperature of 110-115°C and then was broken with wooden mallets into the desired sizes after cooling. S-16 was found to be nonhygroscopic warm or cold up to 60% relative humidity.¹²

APPENDIX C

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